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A new theory of image formation through scattering media was developed, based on Fourier optics & optical information concepts. It predicts the capabilities & limitations of the first arriving light method of imaging through highly scattering media in a way totally different from the conventional one of transport & diffusion theory.A highly generalized theory of optical sectioning by holographic means was carried out.The method shows the similarities between broad source optical sectioning & broad spectrum optical sectioning.An observation is that broad spectrum light gives a broad source effect, tying together the basic van Cittert spatial coherence theory & Wiener-Khinchine temporal coherence theory.We developed a method of non-holographic incoherent optical sectioning that is easily implemented, gives good optical sectioning in reflection & gives second order sectioning in transmission. We invented a new type of confocal imaging system, chirp confocal, that combines technologies from four diverse disciplines: synthetic aperture imaging, chirp pulse compression, holography, & conventional confocal imaging.

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FINAL REPORT

Investigation of Image Formation in Scattering and Other Irregular Media

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ABSTRACT: The theory of imaging through scattering media was extended. A new theory of image formation through scattering media was developed, based on Fourier optics and optical information concepts. It predicts the capabilities and limitations of the first arriving light method of imaging through highly scattering media in a way totally different from the conventional one of transport & diffusion theory. A highly generalized theory of optical sectioning by holographic means was carried out. The method shows the basic similarities between broad source optical sectioning and broad spectrum optical sectioning. An especially intriguing observation is that broad spectrum light gives a broad source effect, thus tying together the basic van Cittert spatial coherence theory and the Wiener-Khinchine temporal coherence theory. We developed a method of non-holographic incoherent optical sectioning that is easily implemented, gives good optical sectioning in reflection, and gives second order sectioning in transmission. We invented a new type of confocal imaging system, the chirp confocal, that combines technologies from four diverse disciplines: synthetic aperture imaging, chirp pulse compression, holography, & conventional confocal imaging. Extensive experimental work was done to verify the ideas that have been developed.

A. Statement of problem studied:

1. Explore new generalized confocal methods and extend the theory of generalized broad spectrum low coherence confocal imaging.
2. Develop new and novel ideas for image formation through scattering media
3. Develop the spatial filter gating method as a tool to investigate the properties of image-bearing light in a scattering medium, for example, the image retrieval process under ultra-short gating times.
4. Analyzed a new invention; the chirp confocal process.

B. Summary of the most important results

1. A new theory of time gated imaging through scattering media was developed, based on the technique of Fourier optics. This approach appears to be new and is a significant departure from the previous theories. It is relatively simple compared to the other methods, is a very physical viewpoint, and yields closed-form solutions. The essence of the method is that diffusion theory and transfer theory are not part of the analysis. Instead, spatial filtering and controlled free space propagation become the basic elements. The specific elements of the process are:

    a. The substitution of a sequence of planar scatterers (or thin scatterers) for the volume scatterer.
    b. The insertion of a 4-F filtering system between the scattering units, and
    c. A chain of equivalences, leading from the aperture to the gate, of

    $$A(x) \rightarrow H(f_x) \rightarrow \Delta\theta \rightarrow \tau$$

    where Ax) is the aperture function, which in its fourier plane position becomes a spatial filter that controls the angular spread $\Delta\theta$ of the propagating light, which in turn finally becomes a time -gate width τ. Overall, this is a rather intricate chain, although each element is rather simple.

    The analysis predicts in a straight-forward wall all of the basic characteristics of time gated imagery in scattering media. The theory predicts a limit on the resolution of process, such that while short pulses, or short coherence light, leads to better resolution, there is a limit beyond which still shorter pulses lead to no improvement in resolution, and in fact leads to catastrophic loss of resolution. This limitation appears as a rising wall against which all of the various gating methods described in the literature are pressed, hence the experimentally-observed fact that all of these methods lead to essentially the same limiting resolution.

    This work was started under the previous ARO grant and completed on the present one. The work is published in the March 2002 issue of Journal of the Optical Society of America. (ref. 9).

2. A generalized theory of coherence confocal imaging was made. Confocal imaging is a method for vastly improving the imaging of thick objects. It is a way of imaging an interior plane of the volume without degrading the focused slice of the object because of defocused light scatterers from other parts of the volume overlaying the focussed part of the image. Put otherwise, it is a way of achieving optical sectioning without degradation from out-of-plane scattering elements. A number of years ago we discovered a holographic way of achieving the same results. This method is sometimes called holographic coherence confocal imaging. We have in the past developed various extensions of this method. The coherence confocal effect is achieved by producing an image plane hologram with light of reduced spatial or temporal coherence.

   We have developed a generalized theory of coherence confocal imaging that unifies, in a simple way, all of the many aspects of this imaging process. It gives particular attention to the use of spectrally broad light to the optical sectioning process. The use of spectrally broad light in this application is not simple; the theory involves such issues as achromatic interferometry and calculation of the optical coherence function, particularly when the illumination system lacks cross spectral purity.

   The theory that we developed has considerable generality, applying to a wide range of situations. It is at the same time quite simple and easy to apply. It avoids the need to incorporate imaging systems into the analysis, and also avoids the most difficult aspects of coherence theory. It does involve the propagation of light beams through systems consisting of multiple diffraction gratings. However, such analyses are readily carried out, either in closed form, or with the aid of a computer. A number of interesting results have been found.

   A particularly interesting conclusion is that a broad spectrum source give a pseudo-broad-source effect, even to the extent of obeying the van Cittert Zernike theory of spatial coherence, but yet retains the basic properties of broad-spectrum interferometry. Or put otherwise, temporal coherence has simulated spatial coherence, yet it still behaves like temporal coherence, in that it also obeys the Wiener Khinchine condition, which is of course the basis for temporal coherence theory. We have carried out the analysis by using paraxial approximation; this produces limitations for practical design, but does not sacrifice the basic concepts that are of principal interest here.

   This work was reported at the SPIE symposium in Orlando, Florida and was published in the proceedings (ref 5) Further work was subsequently reported (refs. 6, 7).

3. Experimental results: A major experimental program was undertaken to verify the basic theories we have developed. An interference microscope was set up on an optical bench, giving magnification up to 400X. Mounted slides of various tissue samples were obtained from the medical school. A professional microscopist, skilled in confocal microscopy, was brought in as an advisor. We concentrated on investigating the case of transmission microscopy rather than reflection. The case of transmission coherence confocal microscopy is relatively unexplored and the theory indicates that this mode gives much weaker sectioning than does the transmission case. In addition, we explored an untried mode, where the object was taken out of the interferometer and placed source-side of the interferometer. For this mode, theory suggests that the optical sectioning effect should be nil, but the experimental results showed considerable improvement of the portion of the image lying at the focal plane. This effect was persistent, being present for a range of slide images. Furthermore, when the hologram recording process was driven to non-linearly, the image formed in the second order was found to bring out some aspects of the image in an interesting and unexpected way. These effects are at present surprising and presently not understood. The results have been reported at an SPIE conference on holography in January 2004. ref.10.

4. The triple correlation process, a technique used in astronomy for imaging through aberrating media such as turbulent atmosphere, has been applied to the process of imaging through scattering media, such as might be found in medical applications, for example, the imaging thorough biological tissue.

5. We invented, analyzed and demonstrated a generalized holography-based approach, with improved spatial resolution, for forming images through a scattering medium. The various angular directions are encoded either with different wavelengths or by capturing their corresponding images in different time slots. The various encoded images are recorded as a digital hologram and then the reconstruction process, along with appropriate image processing, is carried out by computer. The principle was demonstrated by recording image-plane holograms. We suggest that this approach can be combined with the first arriving light method to further improve the results. This work is reported in the paper by Mills, Zalevsky and Leith (ref 8).

6. We carried out a project using non-holographic means to achieve coherence optical sectioning. We considered the optical sectioning that occurs when the object information is sent through both paths of an interferometer instead of only one. This arrangement has several interesting aspects. First, the system is simplified, since the object, occupying both branches of the interferometer, can be removed from the interferometer entirely and can be placed either source-side or detector-side of the interferometer. Both modes are inherently easier to implement than the previous ones, involving the interference of an object beam and a reference beam. The mathematics of this alternative system is significantly different from the holographic one: (a) there is linearity

in intensity, not amplitude and (b) the phase is not preserved in the recording process. Despite the enormous difference, we have shown that the process works, i.e., it produces optical sectioning, but in a rather surprising way. We posed the question, does this arrangement compromise the optical sectioning capability. The answer, obtained in our analysis and supported by experimental verification, is that in the reflection mode (light reflected from the object) there is essentially no loss of performance. On the other hand, for the transmission mode, the optical sectioning still works, but at a significantly lower lever of sectioning capability. This hologram mode has been described in a publication (ref. 12).

Considering the issue of alternative approaches to optical sectioning more broadly, we relate this currently important problem to another that was extensively researched in the 1970's and 1980's. This was to use incoherent light to accomplish the various tasks that had usually been done with coherent light. Many clever configurations were devised to accomplish various tasks, e.g., to make holograms and spatial matched filters with incoherent light, or to produce interference fringes of arbitrary profile, such as sawtooth; such fringes can be recorded to form diffraction gratings of arbitrary groove shape. The motivation was to utilize the redundancy of incoherent light to produce ends results with extremely good signal to noise ratio. The noise that the incoherent light processes suppress result from scattering centers in the optical system, but lying outside the plane of interest. In short, these systems performed a task that was essentially optical sectioning. Thus, a whole new research has now opened up, viz., the use of these various incoherent illumination methods to carry out the currently important task of optical sectioning. This interest now produces the intersection of two important areas of optics, optical and incoherent optical processing. We believe that bringing these two areas together can be quite productive.

7. We invented a new type of confocal imaging system (or microscope). This is the chirp confocal system. Our analysis shows that it works and that it has the advantage that comes with the basic chirp process, namely, that the object can be illuminated with a high energy level without the peak power level being so high as to damage the object specimen. This consideration is important when the specimen is living matter. In addition, further development of the theory indicates that the overall process can be synthesized in a computer, with the result that the data gathering process can be simplified compared to a conventional confocal system, which requires a double scanning process. The further process, including the chirp pulse compression operation, and the second half of the overall scanning process, can be done within the computer. Thus, this new process follows a trend in optical image processing that we have pursued, which is to place as much of the required data processing as possible into the digital computer, with the optical system task limited to data

collection, with the collected data being in the most primitive, pristine form. Ref. 13.

8. The principles of optical sectioning that we have developed, and which are typically applied in the field of microscopy, are inherently applicable on a macroscale, for example, at optical, IR, or microwave wavelengths. We have conceived a system using such a device to image through highly scattering media, or for objects buried in the the ground, e.g., land mines The systems that can be developed at the longer wavelengths, especially microwaves, can have a versatility and adaptability that is not feasible with optical microscopy. The source of radiation can be a phased array antenna, and the spatial decoherentization process could be done using pseudorandom sequences, such as maximal length shift register codes. For example, a shift register code of length N can have many other codes of the same length, all orthogonal. A separate code could be radiated over each of N array elements, thus producing an incoherent extended source with the various elements being pseudo-incoherent instead of incoherent in the usual, optical sense, thus producing possibly better coherence properties. Our interest is to continue to explore this line of investigation.

9. We considered a basic problem—the relation of the synthetic aperture and confocal imaging processes. We showed that, if we regarded the confocal process as the limit of a synthetic aperture process as the source-object and object-detector distances approached zero, the resolution gain of a factor 2 over conventional imaging reduces to about the square root of 2, i.e., if h is the point spread function of a conventional imaging system, then the point spread function of a synthetic aperture system with the same aperture becomes h/2, whereas the corresponding confocal point spread function becomes h squared, which is somewhat narrower than h. We devised a modified synthetic aperture system that is able to produce a confocal effect, or it can alternatively produce a factor 2 of resolution improvement. We have a choice, but we can never have both at once. However, we can have a combination of the two, in which a partial confocal effect is available, with a corresponding partial loss of the factor 2 resolution improvement. (refs. 11, 13).

C. List of papers submitted or published under ARO sponsorship on this grant:

1. Emmett N. Leith, Kurt D. Mills, Louis Deslaurier, Shawn Grannell, Brian G. Hoover, David S. Dilworth, Hsuan Chen, Marian Shih, Joaquin Lopez, and Brian D. Athey, "Information optics concepts applied to image formation in highly scattering media," Proceedings of SPIE, Vol. 4392 (2001).
2. Emmett N. Leith, Kurt D. Mills, David S. Dilworth, Brian D. Athey, and Shawn Grannell, "Holographic methods for imaging into volume media," Proceedings of SPIE, Vol. 4435 (2001).

3. Emmett N. Leith, Kurt D. Mills, Shawn Grannell, David S. Dilworth, Brian D. Athey, and Joaquin Lopez, "Analysis of time-gated imaging through scattering media by a Fourier optics approach," J. Opt. Soc. Am. A/Vol. 19, No. 3/March 2002.
4. Brian G. Hoover, Louis Deslauriers, Shawn M. Grannell, Rizwan E. Ahmed, David S. Dilworth, Brian D. Athey, and Emmett N. Leith, "Correlations among angular wave component amplitudes in elastic multiple-scattering random media," Physical Review E, Volume 65, 026614, 2002.
5. E. N. Leith, K. D. Mills, W. C. Chien, B. D. Athey, and D. S. Dilworth, "A generalization of the theory of holographic coherence confocal imaging," Proceedings of SPIE, 4737, "Holography: A tribute to Yuri Denisyuk and Emmett Leith." Orlando, FL, (April 3-4, 2002)
6. E. N. Leith, W. C. Chien, K. D. Mills, B. D. Athey, and D. S. Dilworth, "Optical sectioning by holographic coherence imaging: a generalized analysis," J. Opt. Soc. A., 20, p. 380, (Feb, 2003)
7. E. N. Leith, K. D. Mills, L. Deslauriers, S. Grannell, B. G. Hoover, D. S. Dilworth, H. Chen, M. Shih, B. D. Athey, and J. Lopez, "Information Optics Concepts Applied to Image Formation in Volume Scattering Media," chapter 1, Optical Information Processing: A Tribute to Adolf Lohmann, H. J. Caulfield ed., SPIE Press, (2002)
8. K. Mills, Z. Zalevsky, and E. Leith, "Holographic generalized first-arriving light approach for resolving images viewed through a scattering medium," Appl. Opt., 41, 11, p. 2116, (April 16, 2002)
9. E. N. Leith, K. D. Mills, S. Grannell, D. S. Dilworth, B. D. Athey, and J. Lopez, "Analysis of time-gated imaging through scattering media by a Fourier optics approach," J. Opt. Soc. A., 19, p. 532, (Mar, 2002)
10. K. Mills, "Holographic low coherence confocal microscopy," in Practical Holography, Proc. SPIE, Vol. 5790. Jan 2004.
11. .K. Mills, "Holographic low coherence confocal microscopy," In Practical holography, Proc. SPIE, 5790 (2004).
12. E. N. Leith, "Holography, synthetic apertures and confocal imaging, cross fertilization," Proceedings of the 7 th Joint Conference on Information Sciences, Sept. 26-30, Research Triangle Park, NC. Ed. P.Wang and A. Menzies.
13. E.. N. Leith, W-C Chien, K. Mills, B. Athey, D. Dilworth, and J. Beals, "Noise suppression and o[ptrical sectioning by non-phase-recording interferomery," Appl. Opt. **43**, 4512-4519 (2004).
14. W-C Chien, Dl Dilworth, Elsom Liu and E. N. Leith, "Synthetic aperture chirp confocal imaging," submitted tp Appl. Opt.

D. List of all participating scientific personnel.

1. Emmett Leith, PI.
2. David. S. Dilworth, visiting professor

3. Brian Athey, Professor, Medical School.
4. James Beals,microcopist, Medical School
5. Brian Hoover, graduate student (PhD at end of 200).
6. Kurt Mills, graduate student (PhD in 2003).
7. W-C. Chien, graduate student
8. Elsom Lou,graduate student
9. Zeev Zalevski, visiting scientist (from Israel).

PhD degree awarded: Kurt Mills, June 2003

E. Report of inventions

We submitted an invention disclosure on the chirp confocal process described in accomplishment 7.